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Engineering Notes

Ion Beam Shepherd for Asteroid Deflection

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I. Introduction

ASTEROID deflection is becoming a key topic in astrodynamics. Although no asteroid has been deflected so far, altering the trajectory of a small-sized asteroid to avoid a catastrophic impact with the Earth has been shown to be, in principle, technically feasible [1], and different techniques, ranging from nuclear detonation to kinetic impact and low-thrust methods, have been proposed [1–3]. Each of these methods shows advantages and drawbacks that, in general, depend on the mass and orbital characteristics of the particular asteroid to be deflected as well as its physical property (porosity, composition, surface reflectivity, etc.) and rotation state.

Among the low-thrust methods, in which the asteroid trajectory is altered by a small and continuous push, a very interesting solution was proposed in 2005 by Lu and Love [4]. The method, named gravity tractor or gravity tugboat, exploits the gravitational interaction between an Earth-threatening asteroid and a spacecraft hovering above its surface to achieve a contactless deflection of the former. In the preceding paper, it was shown that a 20 ton spacecraft could deflect a typical asteroid of about 200-m diameter within one year of hovering time and given a lead time of 20 years. The possibility to predictably change the asteroid orbit with no need of physical attachment and irrespective of the mechanical properties of the asteroid makes the gravity tractor concept one of the preferred deflection strategies for subkilometer asteroids for which the orbit characteristics are known with sufficient time before the predicted impact.

However, while offering the undoubtable advantages previously listed, the gravity tractor concept suffers from at least two major drawbacks.

The first is the need for a massive spacecraft to physically produce the gravitational force required to slowly deflect the asteroid. As will be shown in this Note, in order to achieve a given gravitational pull, a gravity tractor needs to carry a total mass that greatly exceeds the mass required (in terms of propellant and power system mass) to counteract such force with an optimized electric propulsion system. While the extra mass can be used for other spacecraft functions (e.g., scientific payloads), the need to deliver it up to the asteroid orbit will affect the total mission cost significantly.

The second is the need for a continuous control of the spacecraft hovering altitude, which has to be fairly small (a fraction of the asteroid radius) if sufficient force is to be achieved. The instability associated with the hovering equilibrium position and the rotation of the generally irregularly shaped asteroid poses collision risks and complicates the control task.

Recently, the authors have proposed a new propulsion concept [5] in which a highly collimated high-velocity ion beam is produced by an ion thruster onboard a shepherd spacecraft and pointed against a target to modify its orbit and/or attitude with no need for docking. If the ion beam is correctly pointed at the target, the momentum transmitted (ions have been accelerated up to 30 km/s and more onboard spacecraft in past missions) can reach the same magnitude that would be obtained if the target object had the same ion thruster mounted on its own structure. The same concept can be advantageously applied to the contactless deorbiting of space debris in low Earth orbit [6] and Earth geostationary orbit [7], a theme that is gaining considerable interest in space technology. Note that the idea of accelerating a spacecraft with a flux of incident ions was also recently explored by Brown et al. [8], who proposed a lunar-based ion-beam generator to remotely propel spacecraft in the Earth–moon system.

As will be shown in this Note, this concept can be used to alter the trajectory of Earth-threatening asteroids with a much higher efficiency when compared with the gravity tractor concept.

II. Ion-Beam Shepherd Satellite

The concept of ion-beam shepherd (IBS) applied to asteroid deflection is schematized in Fig. 1. The shepherd spacecraft is located not too far from the asteroid, and it is pointing one of its ion thrusters directly at the asteroid surface. The high-velocity ions of the quasi-neutral[‡] plasma emitted by the thruster reach the asteroid surface, transmitting their momentum. Assuming the collision is predominantly inelastic, and that the beam fully intercepts the surface of the asteroid, the latter will undergo a force roughly equal and opposite to the one experienced by the spacecraft. It will then be necessary to have a second ion thruster mounted on the spacecraft to cancel out the total force and keep constant the distance with respect to the asteroid.

In the real case, secondary ions and neutrals are sputtered back from the surface, increasing (in principle) the net momentum transmitted to the asteroid. Yet, their ejection velocities are generally small compared with the ones of the impinging ions [9], so that in the end, the effect on the transmitted force is negligible. On the other hand, a decrease in the total transmitted momentum occurs when part of the ions miss the target due to ion-beam divergence effects and possible beam pointing errors. For the beam to fully intercept the asteroid surface, the hovering distance of the spacecraft must not exceed the value

$$d_{\max} \backsimeq \frac{s}{2\sin\varphi}$$

where s denotes the smaller asteroid dimension and φ is the divergence angle of the beam (Fig. 1).

A state-of-the art ion thruster can reach half-cone divergence angles as low as 15 deg [10], which would allow it, for example, to fully intercept a spherical asteroid at a distance of about twice its diameter.[§] At such distances, the risk of collision is greatly reduced when compared with the case of a closely hovering gravity tractor. At the same time, as will be shown later in the Note, the resulting

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[‡] As is always the case in electric propulsion technology, the plasma leaving the propulsion system is neutralized in order to avoid a net charge to accumulate on the spacecraft.

[§] Note that plasma electron pressure effects, not considered here, may result in a moderate increase in divergence far away from the thruster nozzle.

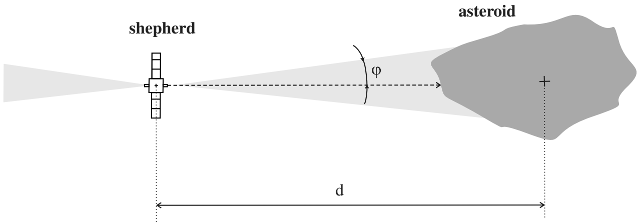

Fig. 1 Schematic of asteroid deflection with an IBS.

gravitational pull would be negligible compared with the force provided by the thruster, hence greatly reducing the instability of the hovering motion, but still large enough to be detected by onboard measurement systems so that it can be used for estimating the distance between the asteroid and the spacecraft.

If one assumes, for simplicity, that the asteroid orbit is quasi circular, the force needed to produce a velocity change ΔV after a hovering time Δt for a spherical asteroid of diameter d_{ast} and density ρ is [4]

$$F_{\mathrm{th}} = 2 \times \frac{\Delta V}{\Delta t} \times \frac{4}{3} \rho \pi (d_{\mathrm{ast}}/2)^3$$

The total propellant mass spent after the hovering time Δt is

$$m_{\mathrm{fuel}} = \frac{2 F_{\mathrm{th}} \Delta t}{v_E}$$

where v_E is the ion ejection velocity, and the initial factor of two takes into account the need for a second thruster to bring to zero the net thrust force on the spacecraft.[¶]

The mass of the spacecraft power plant needed to produce the force $2F_{\mathrm{th}}$ is

$$m_{\mathrm{pp}} = \frac{2 F_{\mathrm{th}} \alpha v_E}{2 \eta}$$

where η is the thruster efficiency and α the inverse specific power (kilograms per watt) of the powerplant feeding the electric propulsion system.

The total spacecraft mass needed to accomplish the deflection is obtained by adding the structure mass m_{str} to the latter two terms:

$$m_{\mathrm{IBS}} = m_{\mathrm{fuel}} + m_{\mathrm{pp}} + m_{\mathrm{str}} = \frac{\pi \rho d_{\mathrm{ast}}^3}{6} \Delta V \left(\frac{2}{v_E} + \frac{\alpha v_E}{\eta \Delta t} \right) + m_{\mathrm{str}}$$

The latter equation can be used to find the optimum value of the ion thruster exhaust velocity, which turns out to be the Irving–Stuhlinger[**] characteristic velocity [11]:

$$v_E^{\mathrm{opt}} = \sqrt{\frac{2 \eta \Delta t}{\alpha}}$$

The IBS mass has to be compared with the one of a gravity tractor achieving the same deflection ΔV after a hovering time Δt, which is [4]

$$m_{GT} = \frac{\Delta V (k d_{\mathrm{ast}}/2)^2}{G \Delta t}$$

where G is the gravitational constant and k is the hovering distance from the asteroid center of mass measured in asteroid radii.

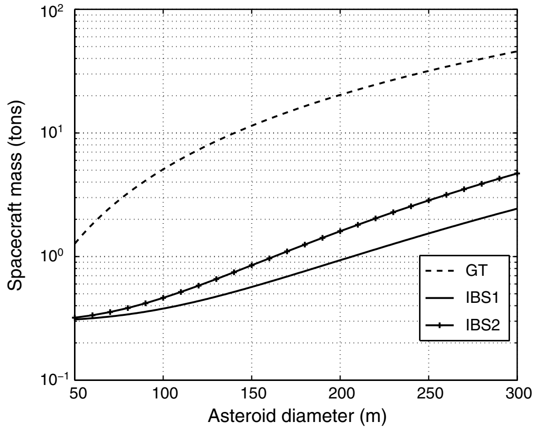

Fig. 2 Total spacecraft mass required for deflecting asteroids of different sizes using the gravity tractor (GT) vs IBS approaches.

A comparison of the total mass required to deflect asteroids of different diameters using the IBS and the gravity tractor concept is shown in Fig. 2, in which the two deflection systems provide, during one year, a velocity change of $1.9 \times 10^{-3}\ \mathrm{ms}^{-1}$, which is enough to deflect a typical asteroid of 200 m given a 20-year lead time [4]. The asteroid is assumed spherical with a mass density of $2000\ \mathrm{kg\,m}^{-3}$ [4]. The gravity tractor is kept at constant hovering distance equal to 1.5 asteroid radii.

Two different propulsion systems are considered for the IBS concept: an advanced propulsion and power system (IBS1), with 80% efficiency, providing 10,000 s specific impulse (which corresponds to the optimum value for a thrust time of one year) and 5 kg/kW inverse power density; as well as a state-of-the-art system [12] (IBS2) with 60% efficiency, 3100 s specific impulse, and 10 kg/kW inverse power density. The structural mass has been set to 200 kg in both cases. Note that assuming a constant power density is correct if a nuclear power plant is employed or if, in case solar power is employed, the asteroid orbit is nearly circular.

In particular, the deflection of a 200-m-diam asteroid, which would require a 20 ton gravity tractor, can be accomplished with an IBS spacecraft weighing less than 1 ton and employing high-efficiency and high-specific impulse ion thrusters available in the near future, or less than 2 ton with state-of-the-art hardware.

Additional plots (Figs. 3 and 4) compare the force transmitted by the ion beam on the asteroid with the gravitational attraction and provide the power level and propellant consumption throughout the deflection mission. The deflection magnitude, asteroid density, and IBS design are the same as in Fig. 2. The IBS hovering distance is set equal to two asteroid diameters from the center.

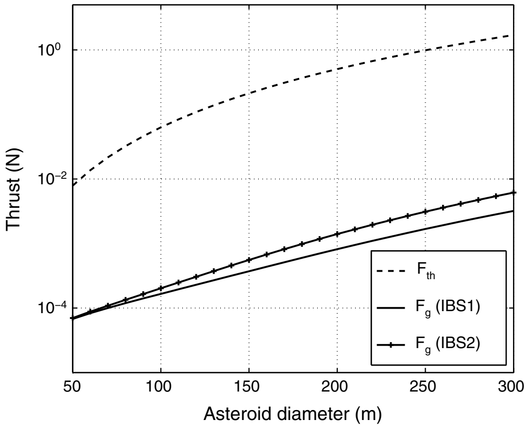

Fig. 3 Comparison between the thrust force F_{th} exerted on the IBS by the asteroid and the mutual gravitational force F_g as a function of the asteroid diameter.

[¶] The additional force needed to deflect the beam shepherd satellite from its original orbit (by the same amount as the asteroid) is clearly negligible.

[**] Note that, in Stuhlinger's book [11], the thruster efficiency is not accounted for in the formula, and the specific power rather than the inverse specific power is employed.

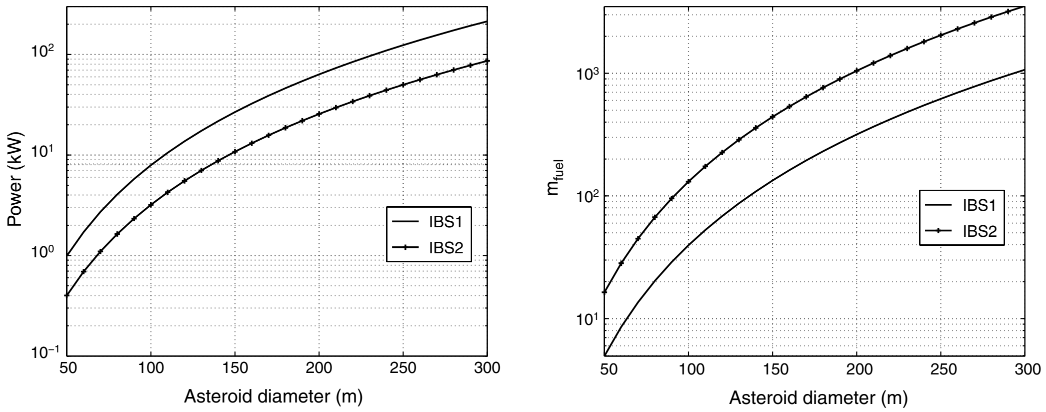

Fig. 4 Power and total propellant consumption for the two IBS designs considered in Fig. 2 and using the same asteroid deflection magnitude and density.

III. Conclusions

A new concept for low-thrust asteroid deflection has been presented that exploits the momentum transmitted by a low-divergence accelerated ion-beam flux from the propulsion system of a nearby spacecraft. Similar to the gravity tractor, the proposed method has the key advantage of contactless deflection capability. However, because the transmitted force is not constrained by the asteroid and spacecraft mass, it can provide more than one order of magnitude mass savings for the same deflection Δ_V. In addition, the required hovering altitude above the asteroid surface can be (depending on the thruster divergence angle) a few times larger than for the gravity tractor, hence greatly simplifying the spacecraft control problem. Given these improvements, and because low-divergence ion beams are routinely employed in spacecraft technology, an asteroid deflection demonstration mission may be within reach in the near future. Future studies will be needed to evaluate the actual deflection performance of the system for different asteroid orbits and to compare it with other short-term deflection methods, such as the kinetic impactor.

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